A Comparison of Electric Power Smoothing Control Methods for the Distributed Generation System

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Abstract—**Renewable energy such as solar light has attracted attention as an alternative energy source to fossil fuel. The output power in photovoltaic generation systems changes steeply. The change in the output power influences the electric power quality of the power system. Therefore, a system that can smoothen the fluctuation of the output power is desired. In this study, we applied the methods of moving average and exponential smoothing to the electric power smoothing control schemes for distributed generation systems and compared their effects. The reduction rate of the power fluctuation and the maximum stored energy of electric double layer capacitors are adopted as the basis for the evaluation methods of the system.**

I. INTRODUCTION

Recently, the problem on resource depletion and the global warming issue have become serious. Therefore, photovoltaic generation (PV) as renewable energy is currently the focus of public attention [1]. However, the output power of PV systems fluctuates steeply with the change in temperature and solar radiation due to weather conditions. Therefore, the PV system may have a negative effect on the power system. Thus, it is necessary to develop some controls to smoothen the generated power of the PV systems.

To compensate for the power fluctuation in the PV systems, a system with electric double layer capacitors (EDLCs) has been proposed [2], [3]. The EDLCs, which are characterized by their fast charging and discharging energy and long lifetime, are useful devices for power smoothing control. However, EDLCs are expensive. Therefore, it is necessary to control power smoothing using EDLCs with the smallest possible capacity. Thus, application of more effective power smoothing control methods is much desired.

The moving average (MA) and the exponential smoothing (ES) methods are applied for the electric power smoothing control. The filter characteristics of the MA and ES methods are derived, and they are verified. To confirm the effectiveness of the power smoothing control methods, a distributed generation power system with EDLCs is simulated by the power electronics circuit simulation software named PSIM. Then, we compare the methods by evaluating the reduction in the EDLCs' capacity without loss in the power smoothing effect.

II. CONFIGURATION OF A DISTRIBUTED GENERATION SYSTEM

A. Distributed Generation System

Fig. 1 shows the configuration of a distributed generation system, which consists of the PV and EDLC systems. The PV system supplies power to the domestic power load, and the surplus power flows back to the grid. At this instant, the backward flow adversely affects the power quality (frequency, voltage, and other parameters) of the power system. Therefore, we establish the EDLC system as a power storage device. In the EDLC system, the power fluctuations can be compensated for by charging and discharging the EDLCs.

B. Electric Power Flow

Let us show the power relationship of the distributed generation system. First, the power relationship equation in the DC link is represented by the following equation:

$$P_{\mathrm{PVsys}} - P_{\mathrm{ECsys}} = P_{\mathrm{PC\_DC}} \ , \qquad (1)$$

where P_{PVsys} is the output power of the PV system, P_{ECsys} is the power of the EDLC system, and $P_{\mathrm{PC\_DC}}$ is the power at the DC side of the power conditioner. η_{PV} is the efficiency of the converter in the PV system, η_{ECsys} is the efficiency of the converter in the EDLC system, η_{INV} is the efficiency of the power conditioner, and η_{EDLC} is the energy efficiency of the EDLC system. Then, in the PV system, the following relationship can be established:

$$P_{\mathrm{PVsys}} = \eta_{\mathrm{PV}} P_{\mathrm{PV}} \ . \qquad (2)$$

The relationship in the charging of the EDLC system is given by Eq. (3).

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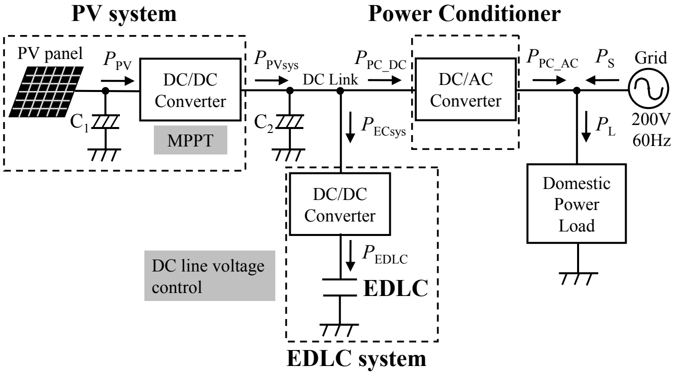


Figure 1. Distributed generation system.

$$P_{EDLC} = \eta_{ECsys} P_{ECsys} \tag{3}$$

On the other hand, the relationship in the discharging of the EDLC system can be expressed as

$$P_{ECsys} = \eta_{ECsys} P_{EDLC} \,. \tag{4}$$

In addition, the relationship at the AC side of the power conditioner can be determined as follows:

$$P_{PC\_AC} = \eta_{INV} P_{PC\_DC} \,. \tag{5}$$

Viewed from the power conditioner to the grid side, we have the following relationship:

$$P_S = P_L - P_{PC\_AC} , \tag{6}$$

where P_{PC_AC} is the power at the AC side of the power conditioner, and P_S is the power from the grid.

III. ELECTRIC POWER CONTROL

A. Photovoltaic Generation System

The output power of a PV system is dependent on the temperature and the solar radiation intensity on the solar cell panel. The PV system is composed of a DC/DC converter and the solar panel. The DC/DC converter can track the maximum power point of the solar cell.

B. Electric Double Layer Capacitor System

The power storage device with the EDLCs is installed in parallel with the PV system. The EDLC system compensates for the sharp fluctuations in the output of the PV system by charging and discharging energy. Further, the DC/DC converter of the EDLC system is controlled so that the DC link voltage v_{DC} is constant.

The power command value P_{ECsys}^* of the EDLC system is determined by the following equation:

$$P_{ECsys}^* = K_{DC}\left\{(V_{DC}^* - v_{DC}) + \frac{1}{T_I}\int (V_{DC}^* - v_{DC})dt\right\} , \tag{7}$$

where K_{DC} is the proportional gain, T_I is the integral time, and V_{DC}^* is the set value voltage of the DC link.

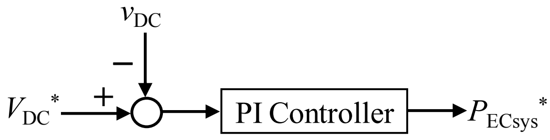


Figure 2. Power command value of the EDLC system.

Fig. 2 shows the power command value of the EDLC system. The DC/DC converter of the EDLC system operates so that the practical power P_{ECsys} coincides with P_{ECsys}^*.

The terminal voltage of the EDLCs v_{EC} is controlled to operate in the range from $V_{ECmax}/4$ to V_{ECmax}. V_{ECmax} is the full charge voltage of the EDLCs. At the instant when v_{EC} reaches V_{ECmax}, the EDLC system stops absorbing energy. At the instant when v_{EC} falls below $V_{ECmax}/4$, the EDLC system stops discharging energy.

The EDLCs charge when P_{PVsys} is greater than the power command value at the DC side of the power conditioner $P_{PC\_DC}^*$. The EDLCs discharge when P_{PVsys} is less than $P_{PC\_DC}^*$.

C. Power Conditioner

The power conditioner smoothens the output power P_{PVsys} of the PV system. The power command value of the power conditioner is derived by the two methods shown in the next chapter.

IV. ELECTRIC POWER SMOOTHING CONTROL

The power command value of the power conditioner P_{PC_DC} is determined to smoothen the output power P_{PVsys} of the PV system. In this study, the MA [4], [5] and ES methods are adopted as the electric power smoothing control methods.

A. Moving Average Method

The power command value of the power conditioner with the MA method is expressed by

$$P_{PC\_DC\_MA}^*(n) = \frac{T_S}{T_M} \sum_{i=n-(N-1)}^{n} P_{PVsys}(i) \ , \tag{8}$$

where T_M is the MA time, N is the number of data, n is the control cycle, and T_S is the sampling time.

The gain characteristic of the MA method is expressed in the following equation:

$$G_{MA}(f) = \frac{T_S}{T_M} \cdot \frac{\sin \pi f T_M}{\sin \pi f T_S} \ , \tag{9}$$

where f is the frequency. The phase characteristic of the MA method is expressed by

$$\phi_{MA}(f) = \tan^{-1}\left\{\frac{X}{Y}\right\} \ , \tag{10}$$

where

$$
\begin{aligned}
X &= \sin 2\pi fT_{\mathrm{M}} \cdot (1-\cos 2\pi fT_{\mathrm{S}}) \\
&\quad - \sin \pi fT_{\mathrm{S}} \cdot (1-\cos 2\pi fT_{\mathrm{M}}) \\
Y &= \sin 2\pi fT_{\mathrm{M}} \cdot \sin 2\pi fT_{\mathrm{S}} \\
&\quad + (1-\cos 2\pi fT_{\mathrm{M}})(1-\cos 2\pi fT_{\mathrm{S}}).
\end{aligned} \tag{11}
$$

The cutoff frequency of the MA method is expressed in the following equation:

$$f_{\mathrm{C\_MA}} = \frac{\sqrt{2}}{\pi T_{\mathrm{M}}}. \tag{12}$$

B. *Exponential Smoothing Method*

The power command value of the power conditioner with the ES method is expressed by

$$
\begin{aligned}
P_{\mathrm{PC\_DC\_ES}}{}^{*}(n) &= \alpha P_{\mathrm{PVsys}}(n) \\
&\quad + (1-\alpha) P_{\mathrm{PC\_DC\_ES}}(n-1)
\end{aligned}, \tag{13}
$$

where α is the smoothing constant from zero to one and n is the control cycle.

The gain characteristic of the ES method is expressed in the following equation:

$$G_{\mathrm{ES}}(f) = \frac{\alpha}{\sqrt{\alpha^2 + 2(\cos 2\pi fT_{\mathrm{S}} - 1)(\alpha - 1)}}. \tag{14}$$

The phase characteristic of the ES method is expressed by

$$\phi_{\mathrm{ES}}(f) = \tan^{-1}\left\{\frac{(\alpha-1)\sin 2\pi fT_{\mathrm{S}}}{(\alpha-1)\cos 2\pi fT_{\mathrm{S}} + 1}\right\}. \tag{15}$$

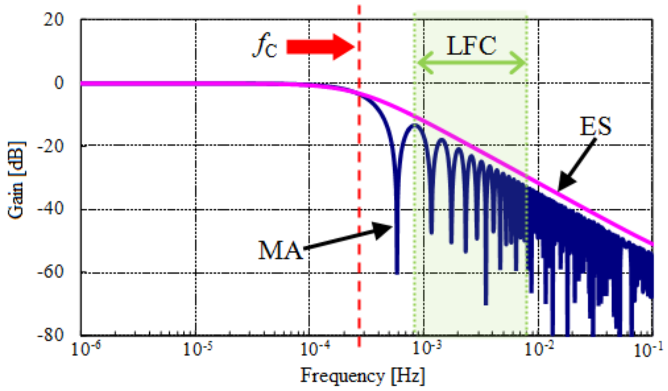
The cutoff frequency of the ES method is expressed in the following equation:

$$f_{\mathrm{C\_ES}} = \frac{1}{2\pi T_{\mathrm{S}}} \cos^{-1}\left\{\frac{\alpha^2}{2(\alpha-1)} + 1\right\}. \tag{16}$$

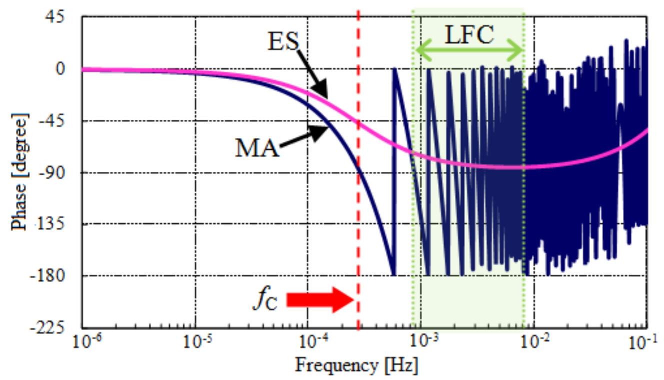
C. *Comparison of the Filter Characteristics of the Moving Average and the Exponential Smoothing Methods*

Fig. 3 shows the filter characteristics of the MA and the ES methods when the cutoff frequency is the same. These filters are designed to require the following conditions: the gain in the load frequency control (LFC) range should be set to -10 dB or lower. The period of the LFC range is from 120 s to 1200 s. Therefore, the MA time calculated by Eq. (9) and decided on 1,700 s, where f = 1/1,200 Hz and T_{S} = 2 s. Then, the cutoff frequency f_{C} is 2.65 × 10^{-4} Hz, as computed from Eq. (12). Fig. 3(a) shows that the gain characteristic of the MA method can be approximated to the first-order lag filter. The smoothing constant α of the ES is 0.00332, which is derived by substituting Eq. (12) in Eq. (16), with T_{M} = 1,700 s and T_{S} = 2 s. The relationship between α and T_{M} can be described by

$$
\begin{aligned}
\alpha &= \cos\frac{2\sqrt{2}T_{\mathrm{S}}}{T_{\mathrm{M}}} - 1 \\
&\quad \pm \sqrt{\left(\cos\frac{2\sqrt{2}T_{\mathrm{S}}}{T_{\mathrm{M}}} - 1\right)\left(\cos\frac{2\sqrt{2}T_{\mathrm{S}}}{T_{\mathrm{M}}} - 3\right)}.
\end{aligned} \tag{17}
$$



(a) Gain characteristics



(b) Phase characteristics

Figure 3. Comparison of the filter characteristics.

The gain characteristic of the ES method can also be approximated to the first-order lag filter because the cutoff frequency of the ES method is coincident with that of the MA method.

Fig. 3(a) shows that the gain of the MA method is lower than that of the ES method. Therefore, the gain characteristic of the ES method can be precisely approximated to the first-order lag filter with a cutoff frequency of 2.65 × 10^{-4} Hz. However, the MA method has a higher gain than the ES method in the range from 1.0 × 10^{-4} Hz to 5.0 × 10^{-4} Hz.

Fig 3(b) shows that the phase of the MA method is smaller than that of the ES method in the range from 1.0 × 10^{-5} Hz to 5.83 × 10^{-4} Hz, i.e., the time lag of the MA method is longer than that of the ES method.

V. ELECTRIC POWER CONTROL SIMULATION

A. *Power Converter Modeling*

To reduce the simulation time, the simulation is performed by replacing the DC/DC converter and the power conditioner of the models by current sources. Fig. 4 shows the model of the power converter. The pair of current sources simulates the behavior of the power converters.

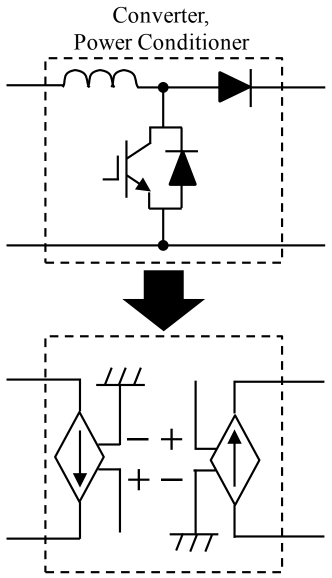


Figure 4. Model of the power converter.

TABLE I. SYSTEM PARAMETERS

Maximum Power of PV	P_{PVmax} [kW]	3.6
Capacitance of Capacitor 1	C_1 [F]	0.00068
Capacitance of Capacitor 2	C_2 [F]	0.0015
Capacitance of EDLC	C_{EDLC} [F]	1,000
Maximum Voltage of EDLC	V_{ECmax} [V]	320
Minimum Voltage of EDLC	V_{ECmin} [V]	80
Setting Value of DC Link	V_{DC}^* [V]	350
Efficiency of DC/DC Converter	η_{PV} [%]	98
Efficiency of DC/DC Converter	η_{ECsys} [%]	98
Efficiency of Power Conditioner	η_{INV} [%]	97
Proportional Gain of PI Control	K_{DC}	6.6
Integral Time of PI Control	T_I [s]	0.01

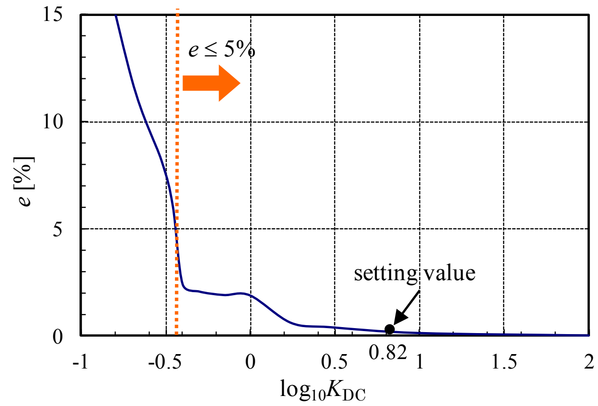


Figure 5. Relationship between K_{DC} and e.

B. System Evaluation

The reduction rate in the power fluctuation is introduced to evaluate the power fluctuation smoothing and is expressed by the following equation:

$$\varepsilon = \frac{P_{con\_max} - P_{pro\_max}}{P_{con\_max}} \times 100 \,, \tag{18}$$

where P_{con_max} is the maximum power fluctuation range of the conventional system, and P_{pro_max} is the maximum power fluctuation range of the proposed system.

The effect of the reduction in the EDLCs' capacity is evaluated by the maximum energy stored in the EDLCs, which is expressed by

$$E_{EC} = \frac{1}{2} C_{EDLC} \left(v_{EC\_max}^2 - v_{EC\_min}^2 \right) , \tag{19}$$

where C_{EDLC} is the capacitance of the EDLCs, and v_{EC_max} and v_{EC_min} are the maximum and the minimum voltages of the EDLCs, respectively.

C. Simulation Results

In this study, we simulated the behavior of the distributed generation system using the simulation software PSIM, developed for power electronic circuits, to verify the effectiveness of the different electric power smoothing control methods and their comparison. Table I shows the system parameters used in the simulation.

Fig. 5 shows the relationship between the proportional gain of the PI controller, K_{DC}, and the error e of the DC link voltage, which is expressed by

$$e = \frac{\left| v_{DC} - V_{DC}^* \right|}{V_{DC}^*} \times 100. \tag{20}$$

Fig. 5 shows that the error becomes smaller with an increase in the gain; however, the system may become unstable when the gain becomes very large. The error is less than 5% when the gain K_{DC} is 0.36, in which $\log_{10} K_{DC}$ is -0.44. On the other hand, the error is almost 0% when the gain K_{DC} is 15.8, in which $\log_{10} K_{DC}$ is 1.2. Consequently, gain K_{DC} is determined at its median value.

Figs. 6 and 7 show the simulation results of the power smoothing control by the MA and the ES methods, respectively. In both figures, P_{PVsys}, which fluctuates steeply, is smoothened by the EDLC system with the electric power smoothing control methods. Waveform P_S shows that the power flowing to the grid is smoothened. Further, the output fluctuation of the PV system is compensated for by the charging and discharging of the EDLCs. Thus, the DC link voltage is controlled to be approximately constant at 350 V.

Fig. 8 shows the FFT analysis results of the waveforms before and after smoothing the fluctuating P_{PVsys} by the MA and the ES methods. The power fluctuation component in the frequency higher than the LFC is reduced to less than 55% by the ES and the MA methods. Further, the power fluctuation component is better suppressed by the MA method than with the ES method; thus, the filter gain of the MA method is

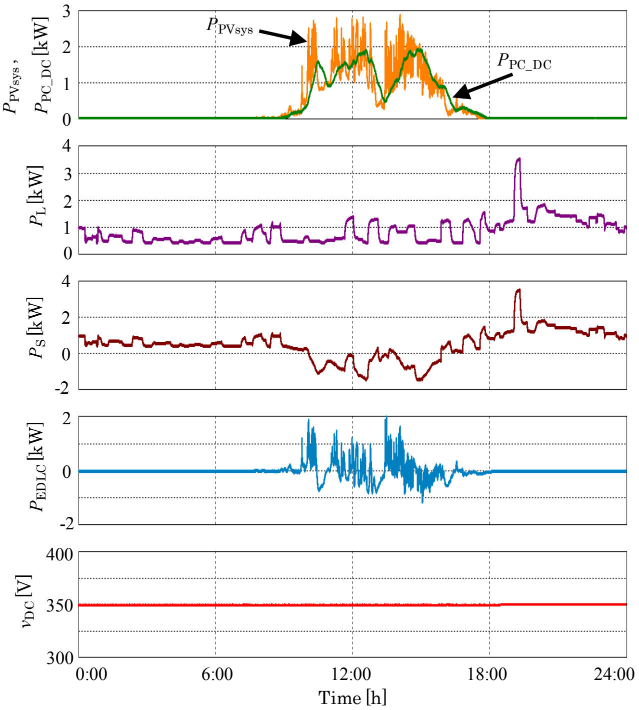


Figure 6. Simulation results by the MA method.

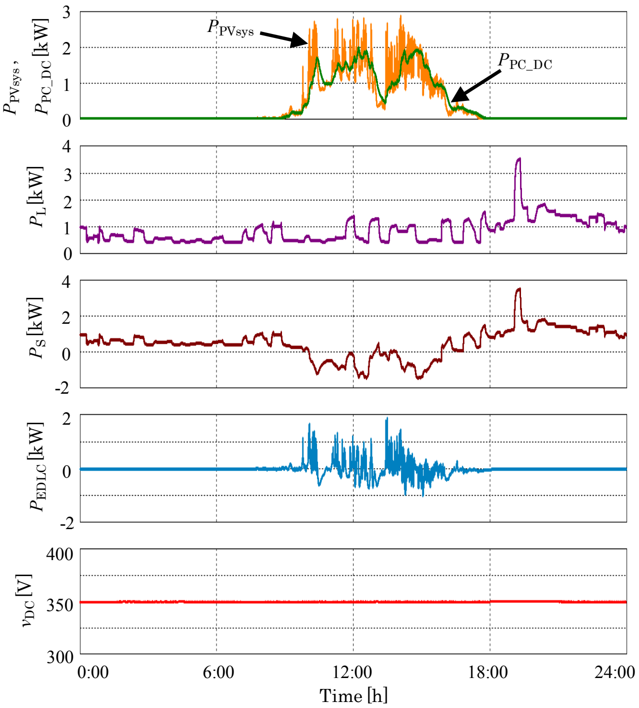


Figure 7. Simulation results by the ES method.

slightly lower than that of the ES method, although it is very small.

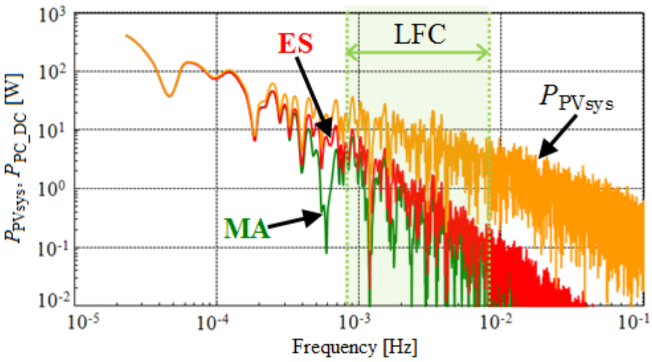


Figure 8. FFT analysis results.

TABLE II. SYSTEM EVALUATION

	MA	ES
ε [%]	45	43
E_{EC} [kJ]	1,687	1,208

Table II summarizes the system evaluation results of the MA and the ES methods. In the case of the MA method, ε is 45% and E_{EC} is 1,687 kJ. In the case of the ES method, ε is 43% and E_{EC} is 1,208 kJ, with a smoothing constant α of 0.00332. When the MA method is used for the electric power smoothing control, ε is 2% higher than that of the ES method because the gain characteristic of the MA method is lower than that of the ES method. Thus, the MA method suppresses the steep power fluctuation component by a greater extent than the ES method. On the other hand, power smoothing by the ES method reduces E_{EC} by 479 kJ as compared with the MA method because the time lag of the ES method is smaller than that of the MA method in the frequency range lower than the LFC. Consequently, we can conclude that the ES method can improve the delay time and significantly reduce the capacity of the EDLCs.

VI. CONCLUSION

This study has investigated the comparison of the MA and the ES methods applied to the electric power smoothing control for distributed generation systems. The simulation results show that the ES method is more effective in the reduction of the EDLCs' capacity than the MA method. The conclusions of this paper are as follows:

1) To suppress the steep fluctuation in the output power of the PV system, the MA and the ES methods are applied as electric power smoothing control methods for the distributed generation system with the EDLC system.

2) The filter characteristics of the MA and the ES methods are derived. Their comparison shows that the gain of the MA method is lower than that of the ES method. On the other hand, the time lag of the ES method is smaller than that of the MA method.

3) From the simulation result, it is found that the reduction rate in the power fluctuation by the MA method is

2% higher than that by the ES method. However, the power smoothing by the ES method reduces E_{EC} by 479 kJ as compared with that by the MA method. We confirmed that the ES method is more effective in reducing the EDLCs' capacity than the MA method.

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